Radio-loud AGN contribution to the Extragalactic Gamma-Ray Background

Debbijoy Bhattacharya
Inter-University Centre for Astronomy& Astrophysics, Pune-411007, India
M. Errando, R. Mukherjee
Barnard College, Columbia University, New York, NY 10027, USA
M. Böttcher
Department of Physics and Astronomy, Ohio University, Athens, OH 45701, USA
P. Sreekumar
Space Astronomy Group, ISRO Satellite Centre, Bangalore, India
R. Misra
Inter-University Centre for Astronomy& Astrophysics, Pune, India
P. Coppi
Department of Astronomy, Yale University, P.O. Box 208101, New Haven, CT 06520, USA

Origin of extragalactic γ-ray background (EGRB) is still a matter of debate. EGRB can either have truly diffuse or unresolved discrete point sources origin. Majority of the Fermi and EGRET detected identified sources are blazar. So, they are expected to be a significant contributors to the EGRB. In order to estimate their contribution to the EGRB one needs to construct their luminosity functions. Here, we examine and construct the evolution and luminosity function of blazars using first LAT AGN catalog. We consider both pure luminosity and pure density evolution models for flat spectrum radio quasars (FSRQs). We also describe the methodology to estimate the contribution from misaligned blazars to the EGRB.

1. Introduction

Observational γ-ray astronomy got a massive boost after the launch of the Fermi Gamma-ray Space Telescope (Fermi) on 11th June, 2008. The Large Area Telescope (LAT) onboard Fermi provides an increase in sensitivity by more than an order of magnitude over EGRET and AGILE.

The origin of extragalactic γ-ray background (EGRB) is one of the fundamental unsolved problem in astrophysics. EGRB can arise from some diffuse processes like black hole evaporation, large scale structure formation, matter-antimatter annihilation, etc (e.g., [1, 2, 3]). Alternatively, due to the limited instrument sensitivity, unresolved γ-ray sources could contribute significantly to the observed EGRB.

Recently, the EGRB has been rederived from Fermi Large Area Telescope (LAT) data [4]. EGRB is consistent with a featureless power law of index (2.41 ± 0.05). The integrated flux above 100 MeV is $(1.03 \pm 0.17) \times 10^{-5}$ photon cm^{-2} s^{-1} sr^{-1}.

Fermi already detected $\sim$ 1500 sources in 11 months of observation (First Fermi catalog; [5]) and is expected to detect many more. In contrast to the less than 100 active galactic nuclei (AGNs) in the EGRET catalog, the first Fermi-LAT AGN catalog [6] consist of $\sim$ 600 blazars. Fermi also detected 11 non-blazar AGN [7], three normal (M 31, LMC and Milky Way) and two starburst galaxies (M 82 and NGC 253). Thus, Fermi provides an excellent opportunity to understand the origin of EGRB.

Since the dominant class of identified EGRET and Fermi sources are blazars, they are expected to contribute to the EGRB. The contribution from blazars to the EGRB is estimated using two different approaches:
(a) Considering a relationship between the blazar γ-ray luminosity with their luminosity at some other wavelength, their γ-ray luminosity function is assumed to be the scaled luminosity function at that wavelength (e.g., [8, 9, 10, 11, 12, 13, 14, 15, 16]).
(b) Constructing the γ-ray luminosity function directly from observed γ-ray blazars (e.g., [17, 18, 19, 20]).

In an earlier work [17, 18] following a similar approach of Chiang & Mukherjee [19] but with almost twice the number of sources, we constructed the γ-ray luminosity functions of flat spectrum radio quasars (FSRQs) and BL Lacs from EGRET-detected sources only. We found strong positive evolution for FSRQs, while BL Lacs did not show any significant evolution. The maximum contribution from blazars to EGRB was found to be $\sim$ 20%. However, due to the limited number of sources in the EGRET catalog, the luminosity function and hence, the contribution from blazars was not well constrained. Mücke & Pohl [21] estimated the contribution from FSRQs and BL Lacs to the EGRB in the context of AGN unification paradigm, and found that unresolved blazars (both "aligned" and "misaligned") contribute $20\% - 40\%$ to the EGRB. In a similar approach, Dermer [22] estimated that FSRQs and BL Lacs contribute $\sim$ $10\% - 15\%$ and $2\% - 3\%$ at 1 GeV respectively. From the first three months of Fermi observation, Abdo et al. [23] found that FSRQs exhibit strong evolution while BL Lacs show no evolution. Using the 1st

Fermi catalog, Abdo et al. [24] found from the source count distribution that the point source contribution is $\sim 16\%$ of the EGRB.

Here, we construct the luminosity function of FSRQs and BL Lacs following the methodology described in Bhattacharya, Sreekumar & Mukherjee [17]. Utilizing the Fermi observed sources we construct a complete source list, apply the V/V_{max} method to search for the presence of evolution, find parameters by modified V/V_{max} method, and finally construct the luminosity function using $1/V_{max}$ method and maximum likelihood estimator.

In the next section we discuss the evolution of blazar source class. We discuss in section 3 the luminosity function construction of FSRQs. The methodology to calculate the misaligned blazars contribution to the EGRB is given in section 4. We conclude with our discussion in section 5.

2. Evolution of blazars

We study the luminosity evolution of blazars by considering a sample that consists of sources from first LAT AGN catalog having 5σ or above detection significance with γ-ray flux (E > 100 MeV) $> 5 \times 10^{-8}$ ph cm^{-2}s^{-1}. Abdo et al. [24] showed that Fermi-LAT detects spectrally hard sources at flux level generally fainter than those of soft sources. They showed that the LAT sample (including all sources) is complete above 7×10^{-8} ph cm^{-2}s^{-1} (Figure 1 of Abdo et al. [24]). However, the maximum photon index for blazars is 2.98, much lower than the maximum photon index of all sources of 1st Fermi catalog, and from figure 1 of Abdo et al. [24], one can see that the blazar sample is complete to a flux below 7×10^{-8} ph cm^{-2}s^{-1}. As a secondary check to the completeness of our sample above 5×10^{-8} ph cm^{-2}s^{-1}, we performed the $< V/V_{max} >$ test of this sample and obtained $< V/V_{max} >$ that matches within 1σ of a sample of limiting flux 7×10^{-8} ph cm^{-2}s^{-1}. Our sample consists of 118 FSRQs. and 39 BL Lacs (25 with known z). The $< V/V_{max} >_{\rm FSRQ}$ comes out to be 0.63 ± 0.03, which indicates strong evolution. For BL Lacs (with known z sources only), $< V/V_{max} >_{\rm BLLac}$ comes out to be 0.49 ± 0.06, which indicates no significant evolution. If we include the sources with unknown z considering they are at the average z of the sample, $< V/V_{max} >_{\rm BLLac}$ comes out to be 0.55 ± 0.05. Since, a good fraction of BL Lacs in our sample do not have redshift information, it is not possible to construct a meaningful luminosity function of BL Lacs at this moment.

We consider both pure luminosity evolution (PLE) and pure density evolution (PDE) for FSRQs.

Both power law ($(1 + z)^{\beta}$) and exponential ($\exp(T(z)/\tau)$) evolution function have been considered. Here $T(z)$ denotes look-back time. The modified $< V/V_{max} >$ method is used to find the evolution parameter. For the optimum parameter value, V/V_{max} is expected to be uniformly distributed between 0 and 1, thus $< V/V_{max} >= 0.5$. We find $\tau_{PLE} = 0.21^{+0.05}_{-0.02}$. For each value of evolution parameter (τ), the distribution of V/V_{max} is compared with a uniform distribution using KS-test which shows distribution of V/V_{max} is uniform for $\tau_{PLE} = 0.21^{+0.05}_{-0.02}$. The optimum value of β_{PLE} is found to be $2.1^{+0.2}_{-0.4}$. Similarly, for pure density evolution, the parameter values of exponential and power law evolution models are, $\tau_{PDE} = 0.17^{+0.07}_{-0.03}$ and $\beta_{PDE} = 3.1^{+0.5}_{-0.8}$ respectively. The upper panel of Fig 1 shows the variation of $< V/V_{max} >$ with different values of power law PDE parameter β_{PDE}. Horizontal dotted lines show the 1σ error in $< V/V_{max} >$.

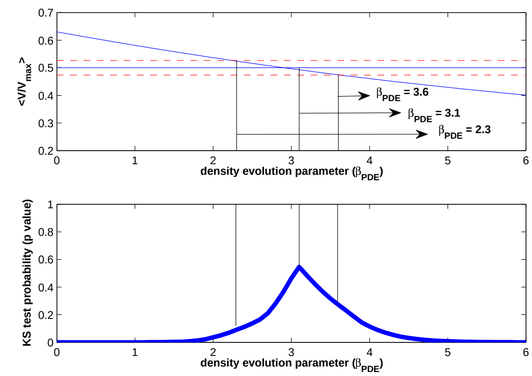

Figure 1: Upper panel: The variation of $< \frac{V}{V_{max}} >$ with evolution parameter β. Lower Panel: The variation of KS test probability with β.

We derived the average γ-ray photon index (s_γ) following the methodology given in [17, 25]. The values of $< s_\gamma >$ for FSRQs and BL Lacs are 2.45 ± 0.16 and 2.17 ± 0.22 respectively.

3. Luminosity function construction of FSRQs

For pure luminosity evolution, after de-evolution of the sources at $z = 0$, we constructed their luminosity function by $1/V_{max}$ method which suggests a luminosity function described by a broken power law. We then used maximum Likelihood function for the redshift distribution of sources, considering a broken power law luminosity function,

$$\begin{aligned} \phi(L_0) &= \phi_0 \times \left(\frac{L_0}{L_B}\right)^{-\alpha_1} \quad L_0 \leq L_B\,, \\ &= \phi_0 \times \left(\frac{L_0}{L_B}\right)^{-\alpha_2} \quad L_0 > L_B\,. \end{aligned} \tag{1}$$

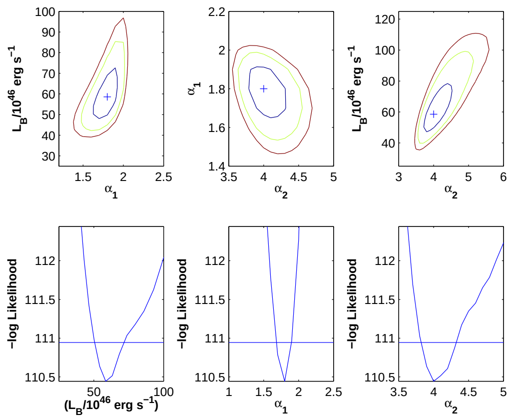

Figure 2: Likelihood parameters contour plot of luminosity function for power law PDE model. Upper Panel: 68.3%, 95.4% and 99% ($\Delta log\mathcal{L} = 1.15, 3.08, 4.61$ respectively) likelihood contour plot (in to out) for α_1, L_B (left), α_1 (middle), α_2 and α_2 (right), L_B. Lower Panel: variation of negative log likelihood values for L_B (left), α_1 (middle) and α_2 (right). the intersections of the solid line with the curve represents the 1σ value.

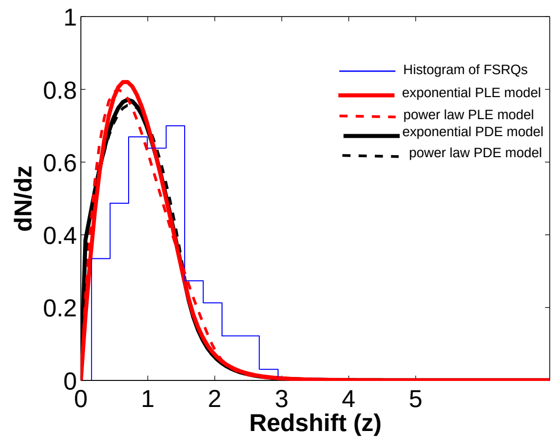

Figure 3: Distribution of FSRQs with redshift. Histogram shows the Fermi observed distribution. The red curves represent PLE models. The black curves represent PDE models. solid and dash curves are exponential and power law models respectively.

Table I Luminosity Function Parameters

	L_B **(in** 10^{46} **erg** $\mathbf{s^{-1}}$**)**	α_1	α_2
τ_{PLE}	$2.48^{+0.82}_{-0.33}$	1.5 ± 0.3	$4.5^{+0.8}_{-0.3}$
β_{PLE}	$11.68^{+2.12}_{-1.61}$	1.5 ± 0.2	$7.1^{+2.4}_{-1.1}$
τ_{PDE}	$61.93^{+21.68}_{-15.20}$	2.0 ± 0.1	$3.7^{+0.4}_{-0.2}$
β_{PDE}	$59.73^{+11.71}_{-9.02}$	1.8 ± 0.1	$4.0^{+0.3}_{-0.2}$

Here $\phi(L_0)$ is the de-evolved luminosity function and ϕ_0 is the normalization of the luminosity function. The break luminosity (L_B) and the lower and upper end index (α_1 and α_2 respectively) are constrained by maximizing the likelihood function.

For pure density evolution, we consider a similar form of luminosity function and constrained the parameters by maximizing the Likelihood function for the redshift distribution of sources.

The derived luminosity function parameters values are given in Table I. Fig 2 shows the contour plots of different luminosity function parameters for power law PDE model.

The normalization constant of luminosity function has been determined by equating the total number of FSRQs in our sample to that expected from the model luminosity function. The source distribution (dN/dz) has been over plotted with the model distribution for PLE and PDE models in Fig 3. Exponential and power law evolution models are considered for both PLE and PDE models.

4. Misaligned blazar contribution

According to the AGN Unification scenario, FR II galaxies are the parent population of FSRQs whereas, FR I galaxies are the parent population of BL Lacs. The AGN jet emission is expected to fall very rapidly with increasing jet to line-of-sight angle. Nevertheless, considering the large population of these misaligned blazars compared to nearly-aligned ones, these sources could contribute significantly to EGRB. Fermi has already detected 11 misaligned blazars.

The observed jet luminosity $L(\theta)$ at a jet to line-of-sight angle (θ) can be written as

$$L(\theta) = L(0) \times \xi(\theta) \tag{2}$$

From the knowledge of $\xi(\theta)$ one can in principle, estimate the contribution from off-axis AGNs to the EGRB.

4.1. Construction of $\xi(\theta)$

Our aim is to model the SED of all Fermi-detected off-axis sources using standard leptonic models with structured jets. From the knowledge of these SED modeling and VLBI observations one can fix the emission processes in the jet and other jet parameters and can construct $\xi(\theta)$. Next step is to constrain $\xi(\theta)$ by comparing γ-ray detected misaligned blazars with equivalent on-axis objects (by matching sources with similar jet power, Γ) and then validate our predictions by modeling few misaligned blazars that are not detected by Fermi.

From the observed γ-ray luminosities of off-axis sources and their jet inclination angle one can also construct $\xi(\theta)$. The difference in the observed γ-ray

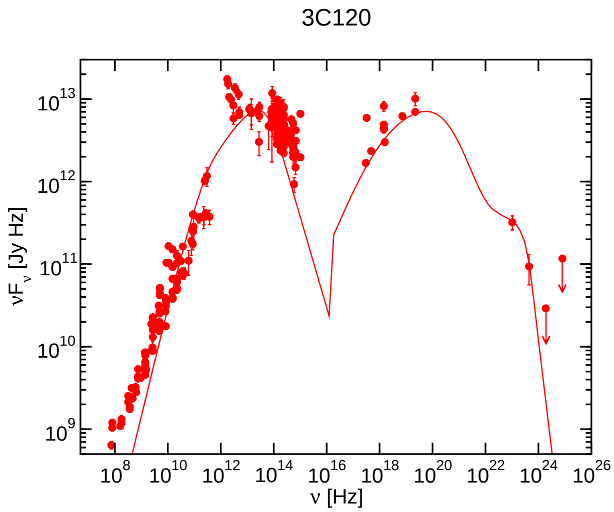

Figure 4: SED modeling of misaligned blazars 3C 120

luminosities between two radio galaxies can arise from two different reasons:
a) due to their different jet to line-of-sight angle,
b) due to their different intrinsic luminosities.

If one considers that the total radio luminosity is a tracer of unbeamed luminosity, then after an appropriate scaling, one can construct $\xi(\theta)$ from scaled γ-ray luminosities and jet inclination angles of off-axis sources.

We have initiated this work. Our aim is to analyze Fermi data to date on radio galaxies and model it to derive jet parameters. We have completed the analysis and the SED modeling of 3C111 and 3C120 (Figure 4 shows the SED fitting of 3C 120.)

Both the sources are well fitted with simple SSC emission model. Γ is also $\sim$5 for both the sources.

5. Discussion

Using first Fermi catalog, we investigated the luminosity function and nature of evolution of FSRQs and BL Lacs separately in γ-rays. The nature of evolution of FSRQs and BL Lacs as found in this work, are in agreement with earlier works (e.g., [17, 19]). We considered both PLE and PDE models for FSRQs. Both power law and exponential evolution functions have been considered. The luminosity function is considered to be of a broken power law form and the parameters are found using likelihood analysis. From this analysis it is not possible to strongly conclude on the true evolution model. Fig 3 suggests that PDE model explains observations marginally better than that of PLE model. In contrast to earlier works of determination of luminosity function from γ-ray observations [17, 19, 20], our derived luminosity function is well constrained. In a recent work, Ajello et al. [26] showed that the redshift of the peak in the number density of FSRQs is luminosity dependent. Hence, they considered luminosity dependent density evolution for FSRQs (similar to that of radio-quiet AGN). They considered a much lower limiting flux ($\sim 10^{-8}$ ph cm^{-2} s^{-1}) and hence, a much larger sample (186 FSRQs) than us.

For misaligned blazars, we plan for SED fitting of all detected off-axis sources and then construct $\xi(\theta)$ from model. This work is under progress and will be reported elsewhere.

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